General Calibration Goals

- Categories
- Measurements

Josh Klein
Penn

Categories

Calibrations basically do four things:

1. Provide corrections to data (e.g., channel gain)
2. Measure parameters of a detector model (e.g., E-field)
3. Measure efficiencies and acceptances if not provided by model
4. Provide tests of the model and resulting uncertainty estimates

Category 4 can make up for a lot of "sins" if test ~ data

We do not have (yet) detailed ties between high-level requirements and knowledge of calibration parameters:

Fiducial volume better than 1%=1% knowledge of v_d everywhere
What does that mean for field map?

Energy bias better than 1%=1% on recombination*lifetime*gain*…

Categories

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Any proposed calibration source should provide motivation in the context of these categories.

DUNE FD Exceptionalism

FD differs from other long-baseline oscillation experiments:

- Cosmic rate through 10 kt is tiny compared to NOvA
- FD is not physically segmented like NOvA or MINOS
- FD ex situ TPC calibrations not possible
- FD response changes differently from NOvA or MINOS
- FD is not truly monolithic like Super-K
- DUNE will not have serious test-beam results at Day 0
- DUNE unlikely to have a functionally equivalent ND

Reconstruction and cut efficiencies on events of interest will be done <u>exclusively</u> with Monte Carlo or extrapolations from tagged events using Monte Carlo.

DUNE FD Exceptionalism

FD differs from other LAr-TPCs:

- Space charge not expected to be an issue
- No cosmic tracker
- No laser system
- No nearby beam instrumentation

There is a belief amongst some that other than electronics, model parameters will be universal or depend only on T, purity, and field design. So MicroBooNE, protoDUNE, LArIAT calibrations and be applied directly to FD---no need to repeat or check!

[I am not yet convinced.]

TPC Calibration of Model Parameters

https://indico.fnal.gov/conferenceDisplay.py?confId=13269

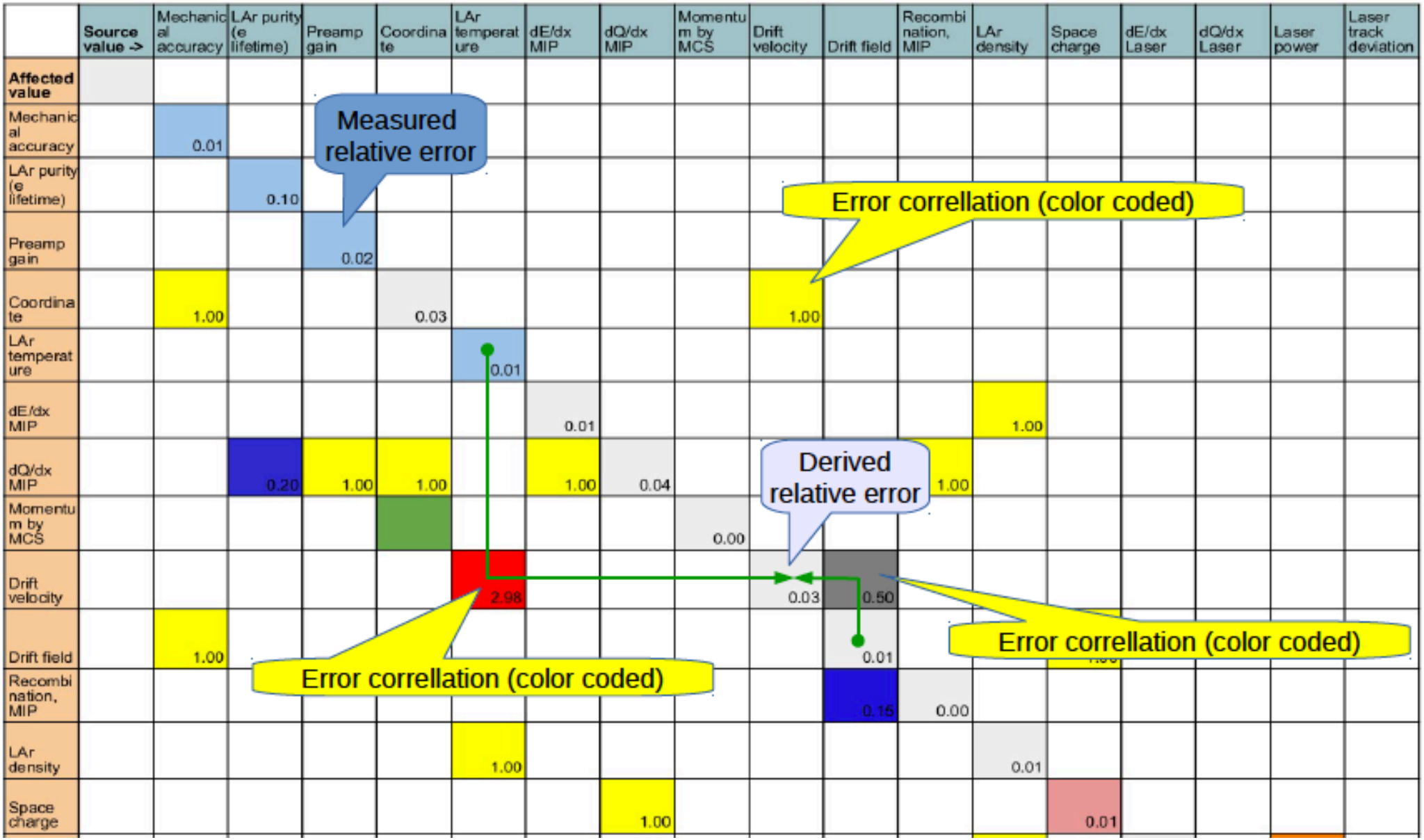
Roughly in order of what we can/must measure first

I. Argon ionization energy (w)
II. Channel gain
III. Overall electronics transfer function (e.g., "shaping")
IV. Electronics noise, including correlated noise (could be "correction")
V. ADC differential and integral linearity
VI. Wire positions and geometry
VII. Electron drift velocity v(x,y,z,t)
VIII. t0 offsets
IX. Electron Lifetime τ(x,y,z,t)
X. Recombination parameters
XI. Longitudinal and transverse diffusion
XII. Temperature map T(x,y,z,t)
XIII. Full Field Map **E**(x,y,z,t)
XIV. Wire field response (particularly for u/v)
XV. Overall energy scale (ADC→dE/dx)

There are non-trivial correlations between these things.

Response Parameter Correlations

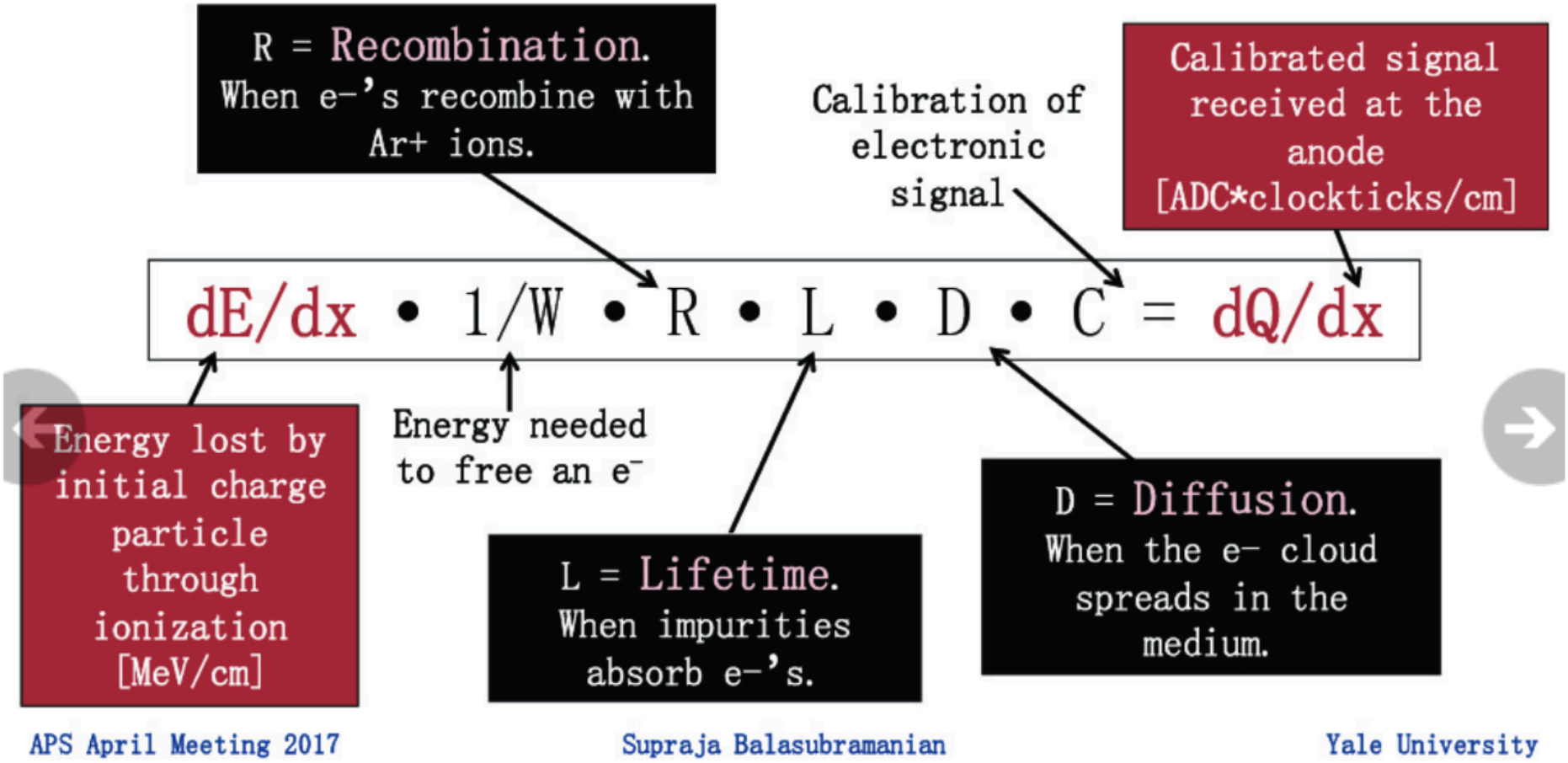
Igor's Matrix



But also: Noise model, FE response (beyond gain), induction wire resp.

Correlations

Example: Calorimetry



Note that there is even a dependence on vd (or E,T) for tracks that are not parallel to the wire because $dx \sim |dy+dz+v_d t|$

Parameter Classes

1. Universal: Completely determined *ex situ*

- Ionization energy
- Wire field response?
- ADC response? (not yet)
- Electronics transfer function?
- Recombination?

2. Calculable: Completely determined by others

- $v_d(E(x,y,z,t),T(x,y,z,t))$
- Overall energy scale (=dQ/dx)?
- $E(x,y,z,t)=E=\Delta V/d$?
- Diffusion?

3. Measured: Requires *in situ* measurement

- T(x,y,z,t)
- E(x,y,z,t) probably
- Diffusion probably
- t_0 Offsets
- Wire positions and geometry
- Electronics noise and pickup

Parameter Classes

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   - Ionization energy
   - Wire field response?
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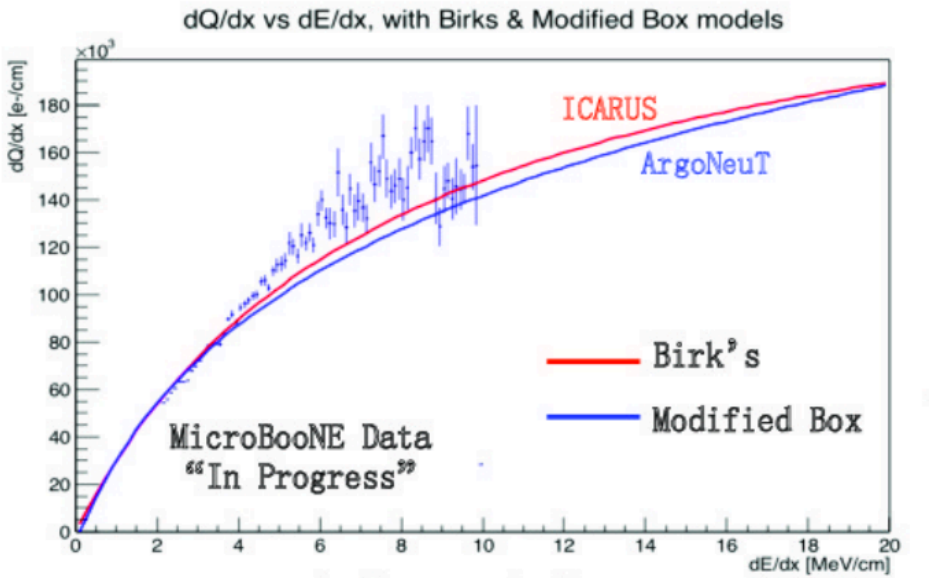
   - $T(x,y,z,t)$
   - $E(x,y,z,t)$ probably
   - Diffusion probably
   - t_0 Offsets
   - Wire positions and geometry
   - Electronics noise and pickup

Assumptions about 1 and 2 and ignorance of those under 3 are OK if there is a precision, relevant test of the model that provides acceptable agreement. If it does not---prepare to figure out why.

Need for in-situ Calibrations and Tests

Even with everything else calibrated, MicroBooNE recombination is different from ICARUS and ArgoNEUT

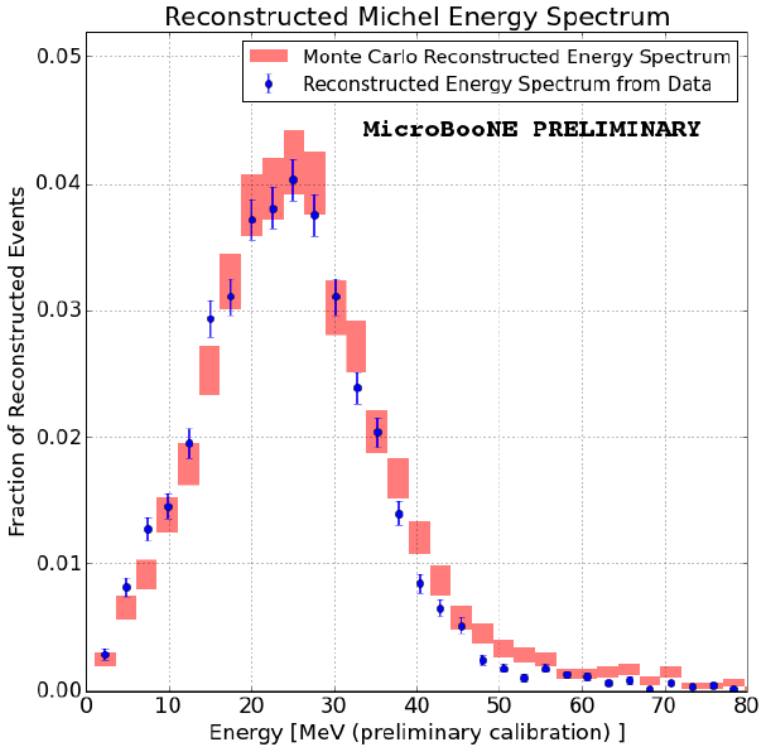


dQ/dx vs. dE/dx,
overlaid with the Birk's and Modified Box models

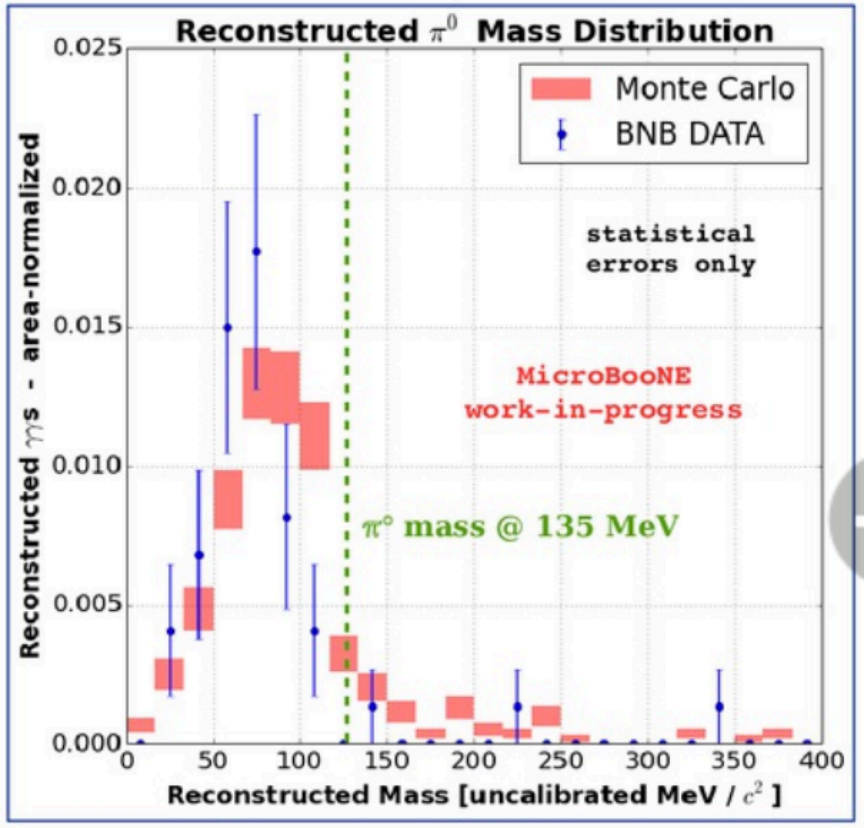
Supraja Balasubramanian

Need for in-situ Calibrations and Tests

MicroBooNE tests do not yet agree at precision level with MC



MICROBOONE-NOTE-1008-PUB
8/25/2016



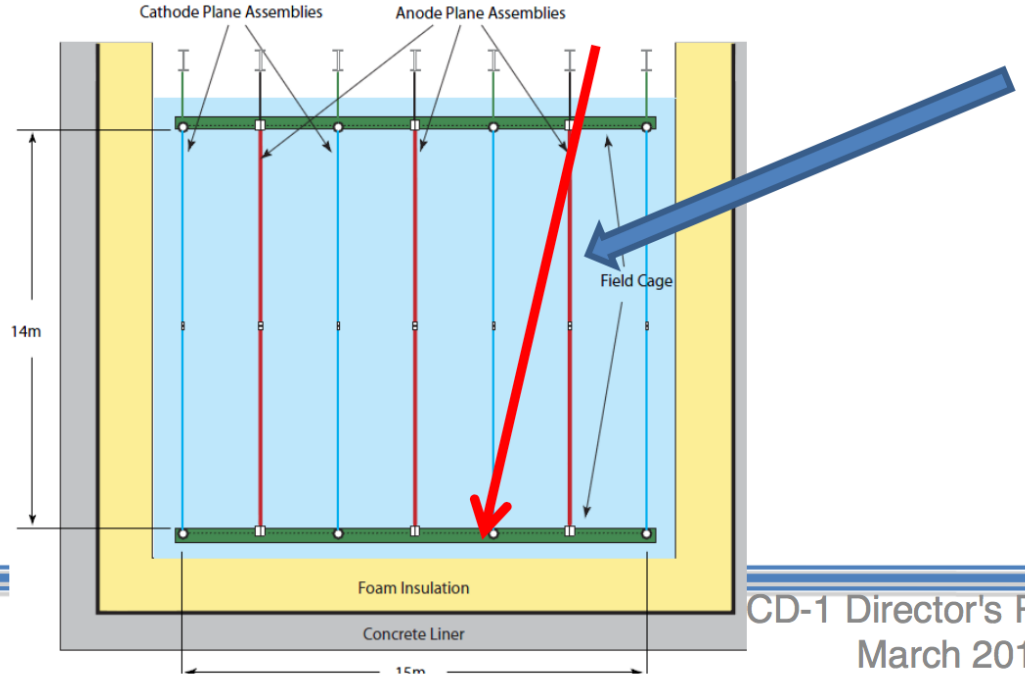
If a test fails, what do you do?

Need ability to figure out why.

David Caratelli, APS meeting

How Much Averaging is OK?

Determining the average response is a lot easier than the differential response---assumptions about uniformity of response lead to things like:



– An accurate measure of τ can be made using one μ at >15°

How Much Averaging is OK?

- Average response works for first-moment uncertainties:

Integrating energy scale determination over x,y,z,t is fine if you integrate the same distribution as data will have.

- But not for higher moments and tails:

Leakage of background and background shape could depend strongly on overall response variation across detector.

How Much Extrapolation is OK?

- Does reconstruction “efficiency” measured with APA/CPA crossing cosmics apply to neutrino events? How do we know that?
- Can measurements of response to hadrons by LArIAT and ProtoDUNE be translated to FD? How? With what uncertainty?
- Can particle ID accuracy determined (maybe, we hope) by ND be extrapolated to FD, despite different readout schemes?

Results of Calibration "Tests"

I. Position reconstruction biases and uncertainties compared to MC model
II. Direction reconstruction biases and uncertainties
III. Energy scale biases and uncertainties
IV. Energy resolution biases and uncertainties

Results of Calibration “Efficiencies”

I. Particle ID efficiencies
II. Noise removal efficiencies
III. Other instrumental effect removal efficiencies

Calibration "Source" Options

For model parameter measurements:

- Purity monitors
- Temperature monitors
- Survey
- Current monitors
- Michel electrons
- Stopping muons
- Throughgoing muons
- ^{39}Ar
- Laser system
- CRT tagger
- Other radioactivity

For model Tests:

- Michel electrons
- π^0 mass peak
- Other decays (K^0s…)
- Tagged events

Backups

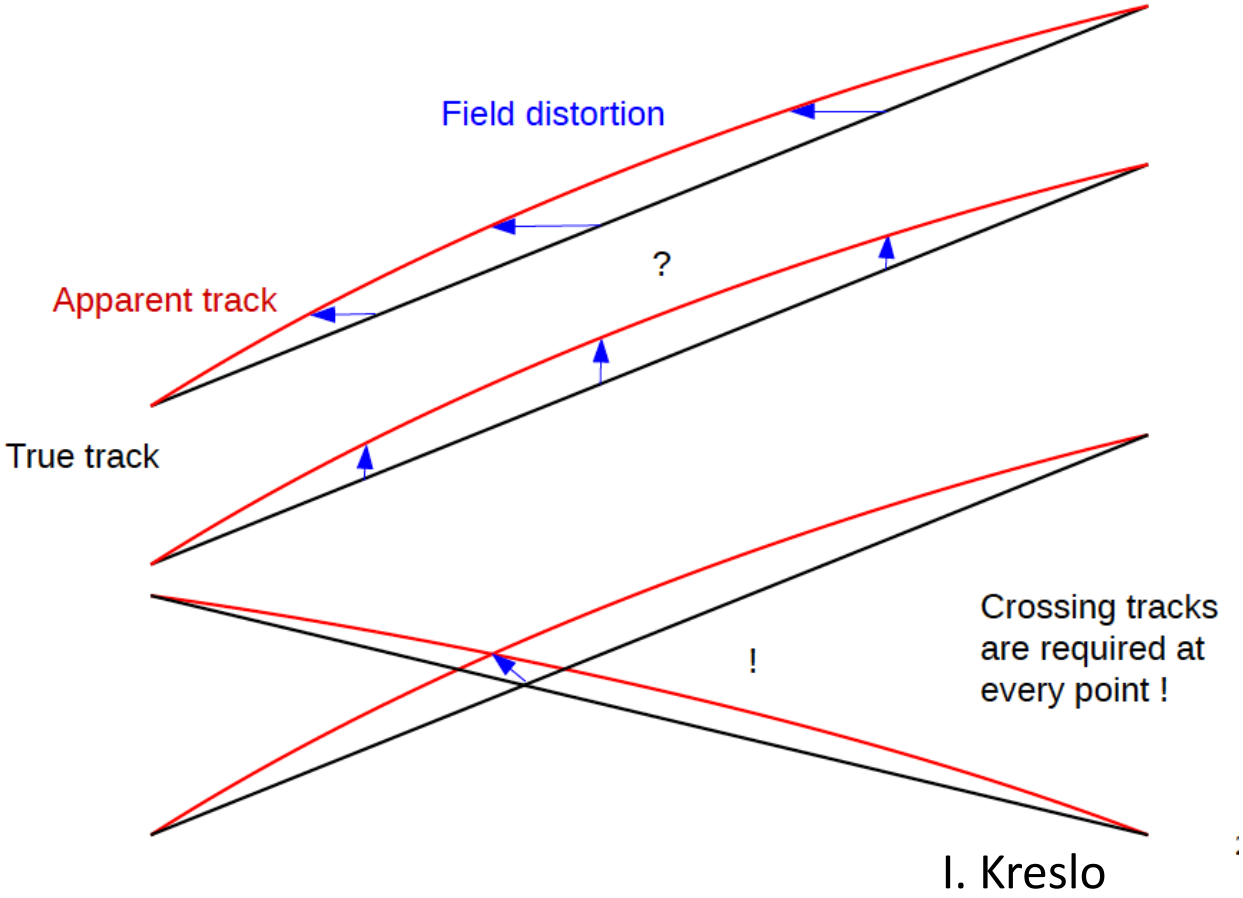
“Monitors” (Purity, Temperature…)

These will be helpful to bootstrap other measurements

But to date they have not successfully produced a “dead-reckoned” model.

Electric Field Measurements

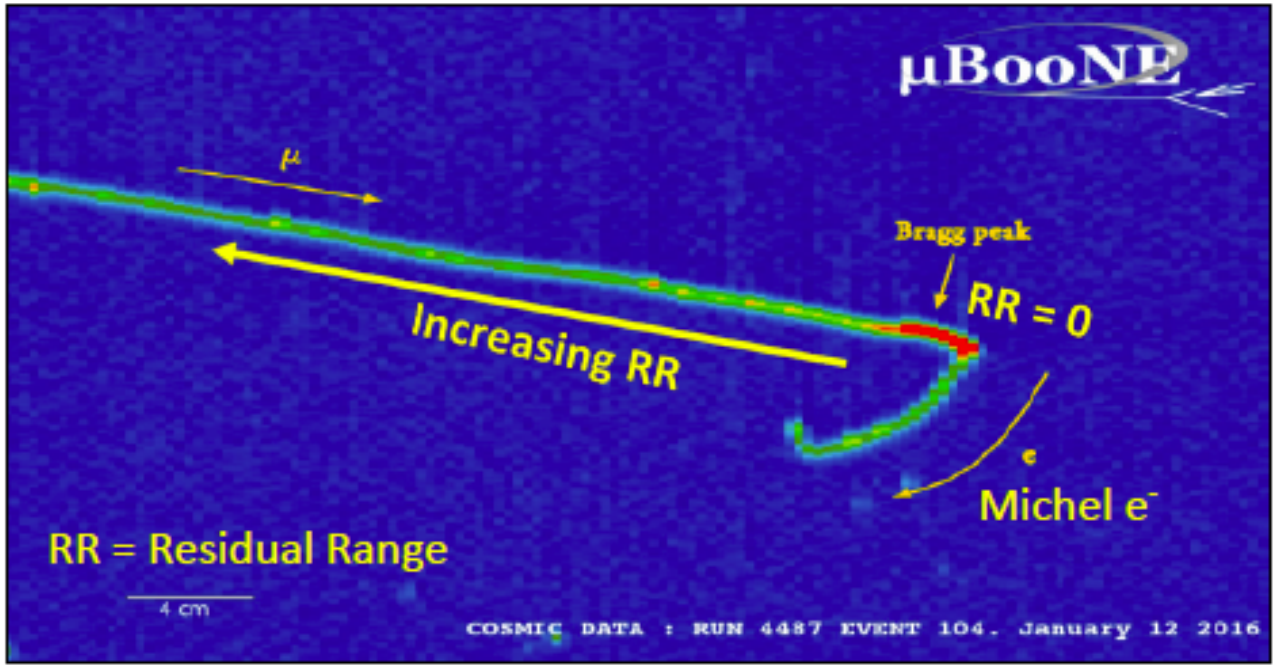
Measuring distortion vector with tracks:



To get a unique field map, need crossing tracks from something.

Michels

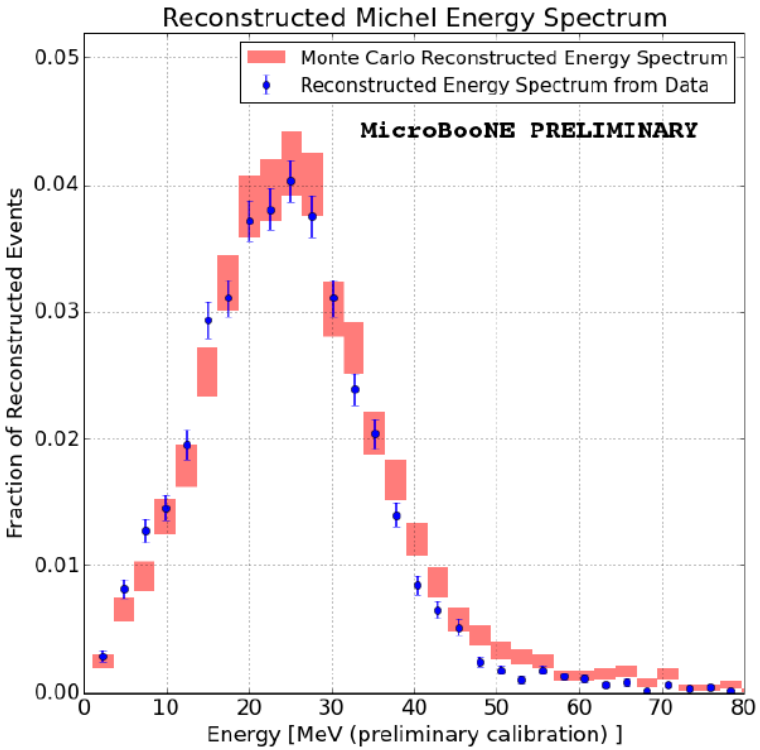
Easy to identify for many geometries:



Could be used to get one parameter if all others already known (e.g., "global" dE/dx scale) but probably better as a test or source for global E scale systematics.

Michels

But precision will be limited:



MICROBOONE-NOTE-1008-PUB
8/25/2016

- Cosmic rate at DUNE is 0.05 Hz/10 kt
- Stopping fraction is about 1%
- Decay fraction about 2/3

So each day there are ~30 Michels/day (assuming we trigger on all of them)

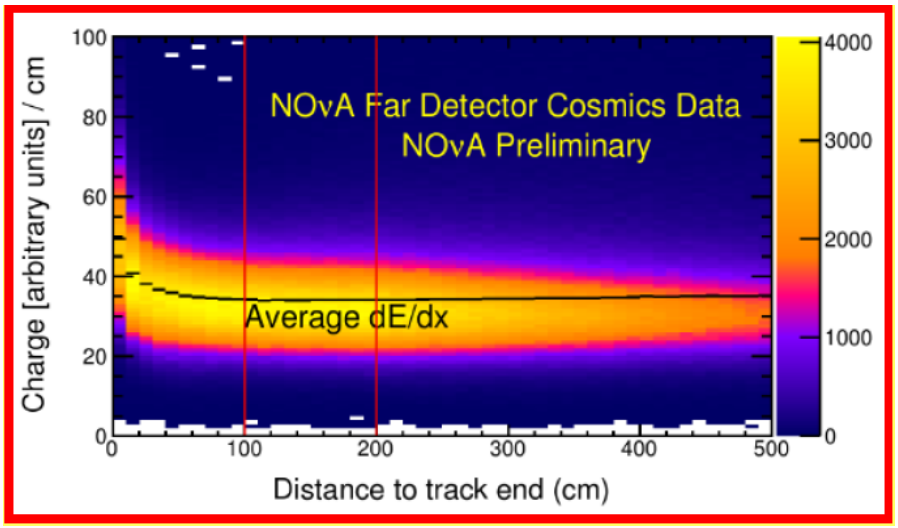
MicroBooNE cuts remove 25% of ID'd Michels (not sure what fraction of Michel's are ID'd---assume 100%)

To get 1% precision (assuming good agreement) we need
0.01 x 25 MeV = 0.25 MeV (mean is ~25 MeV)
0.25 MeV ~=10 MeV/sqrt(1600) (σ is about 10 MeV)
Or 1600 Michels in every relevant "voxel" of detector, for every relevant time interval, for every relevant track geometry.

If we wanted this in every m^3 we need to integrate for ~700,000 days

Stopping Muons

Successful in MINOS and NOvA for measuring dE/dx scale



Meter and more from stopping point is clean MIP region (can probably use more).

Requires t0 and 4 out of:

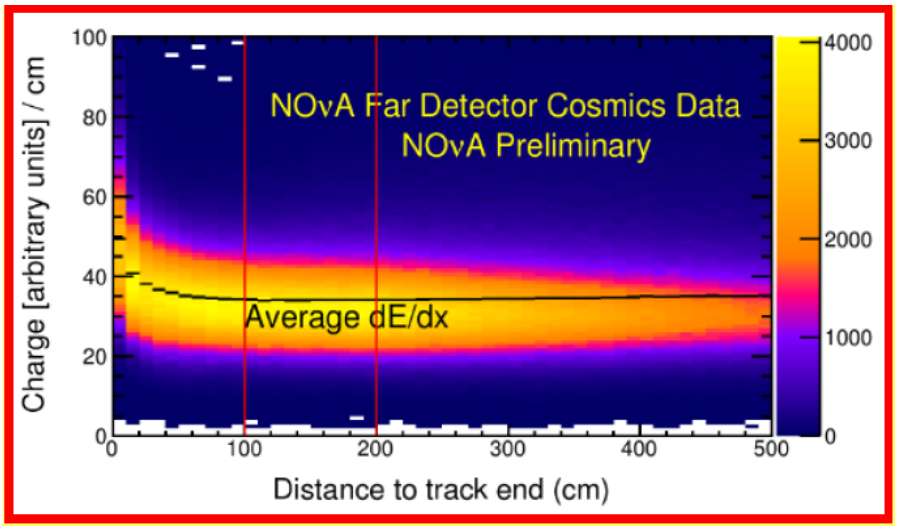
1. Electronics calibrations
2. Knowledge of drift velocity and detector field map
3. Calibrated recombination correction
4. Calibrated electron lifetime as a function of x,y,z,t
5. Diffusion corrections

Or, at least independent knowledge that some of these are negligible

A CRT would reduce requirement for 2 above

Stopping Muons

Successful in MINOS and NOvA for measuring dE/dx scale



Statistics:

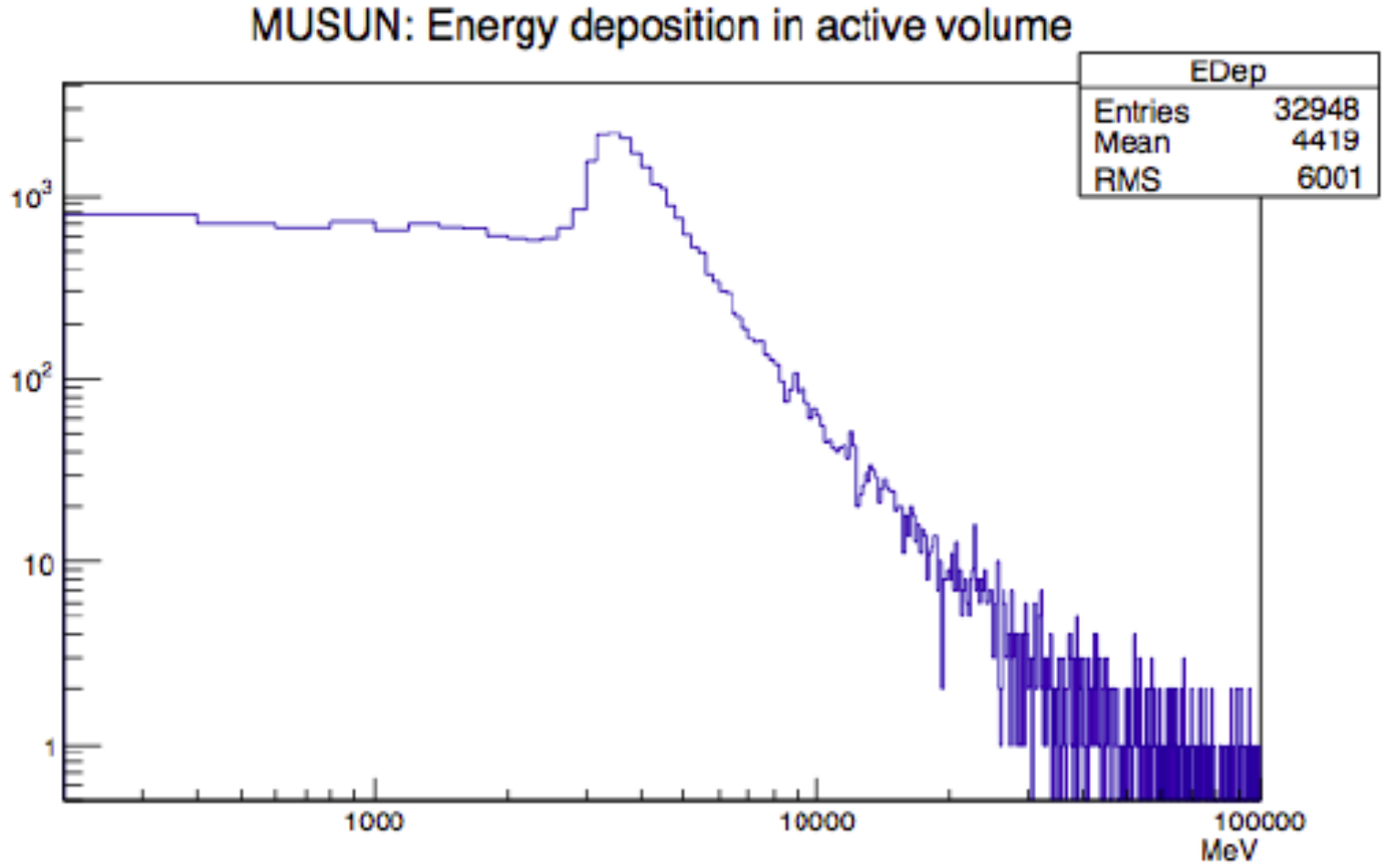
- 0.05 Hz of stopping
- Tag with Michels if no CRT
- 30/day before cuts

Most of the stopping muons stop near the top, but if we ignore this, can use each to calibrate a fairly large volume, so can think of this as scaling by area, not volume.

So to cover ~1000 m^2 need >40 days for one stopper in each bin
Complete requirement depends on resolution and desired precision, as well as time dependence.

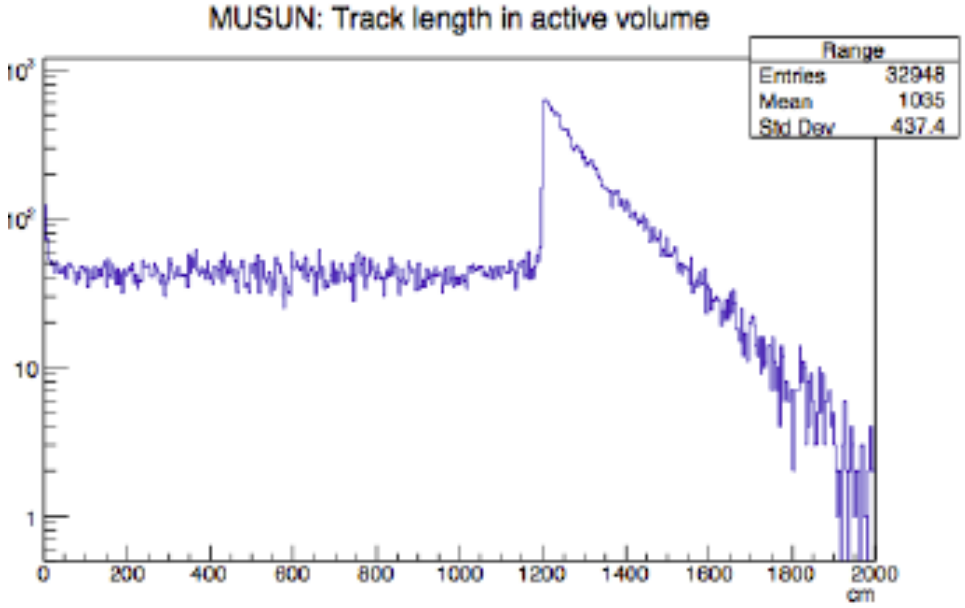
Throughgoing Muons

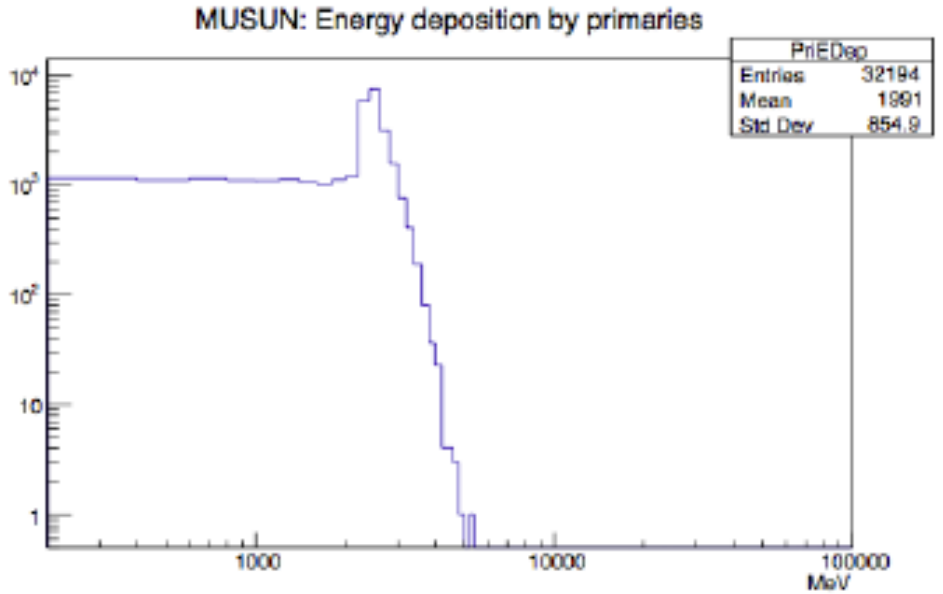
Downward

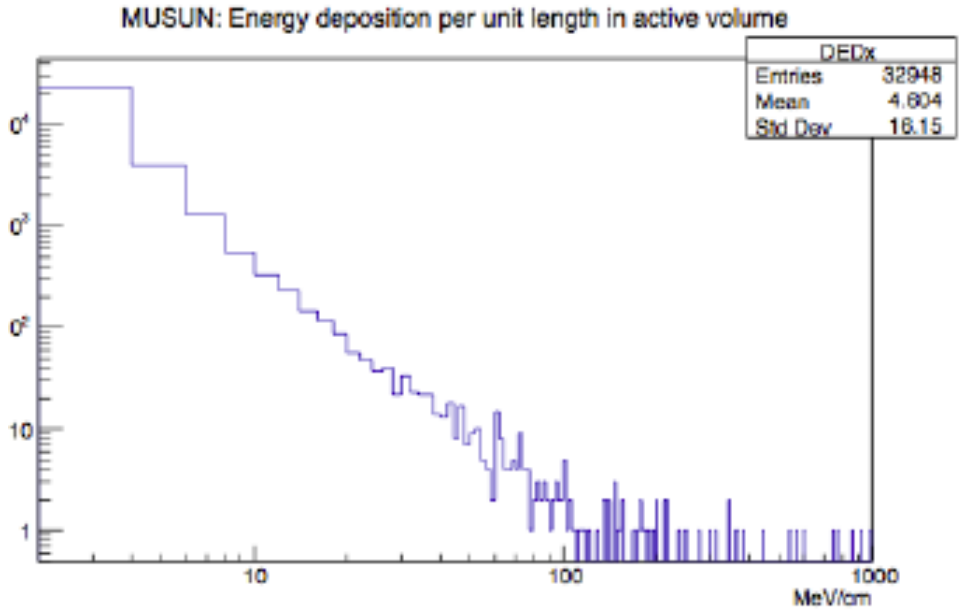


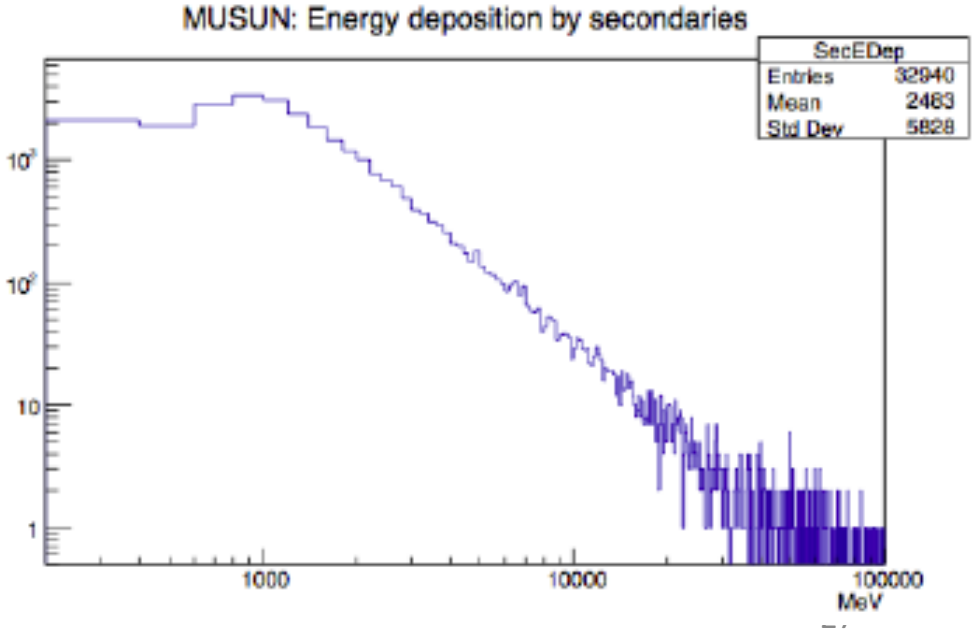
Throughgoing Muons

Downward









Throughgoing Muons

Downward

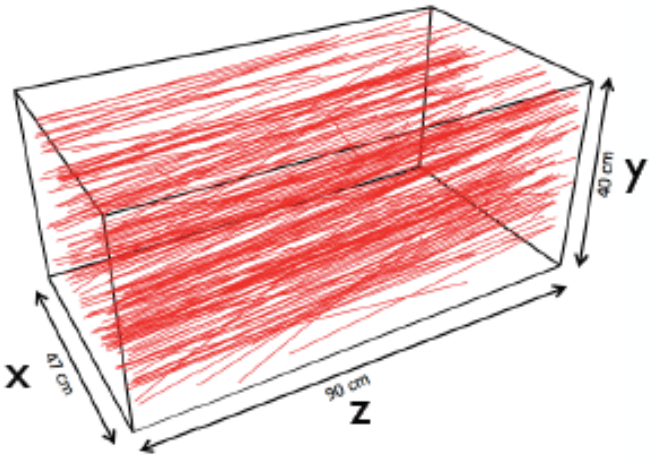
- Illuminates area, not volume, and can use all of them.
- For 1000 m^2, get 4 throughgoing/day in each m^2.
- If we need to populate the peak, then this is reduced
- Uncertainty on dE/dx will depend on simulation of cosmics and propagation
- Full statistics will depend on resolution and requirements.
- As a monitor, will be statistically limited unless we average over larger area/volume

Throughgoing Muons

Downward

BUT, with these statistics can also get:

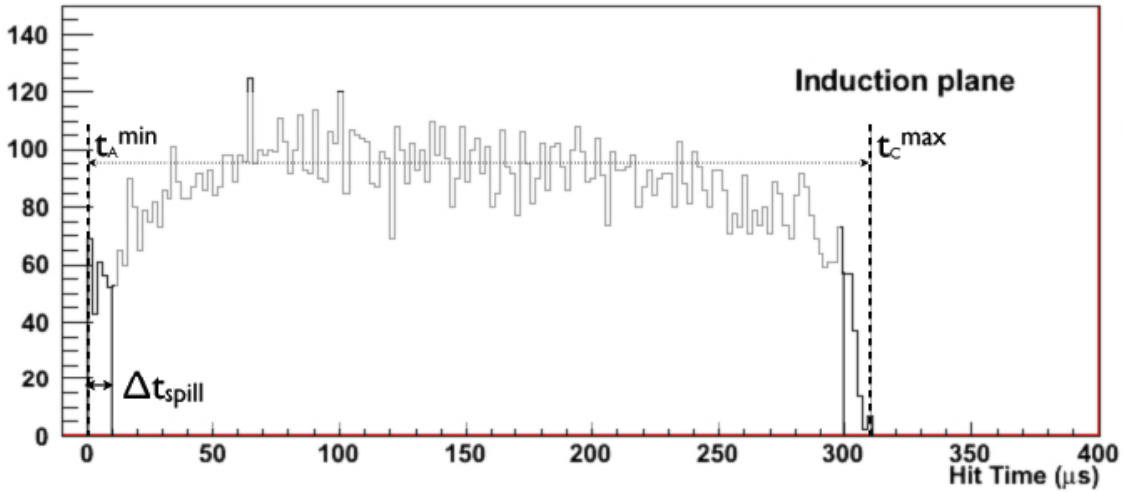
- Average drift velocity across detector a la ARGONEUT

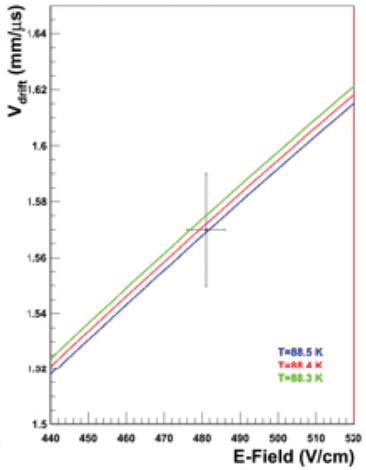


This would be more precise with a CRT

$$t_d = t_C^{max} - t_I^{min} - \Delta t_{spill} = 300.5\ \mu s$$

$$v_d = \frac{\ell_d + \ell_g / r_{T1} - \Delta\ell}{t_d} = 1.57 \pm 0.02\ \text{mm}/\mu s$$



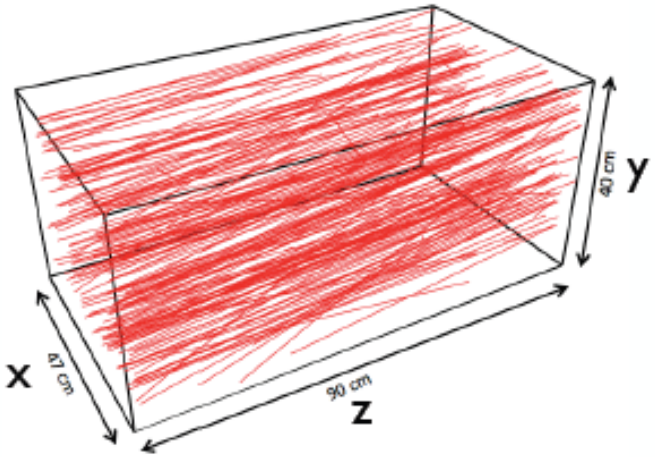


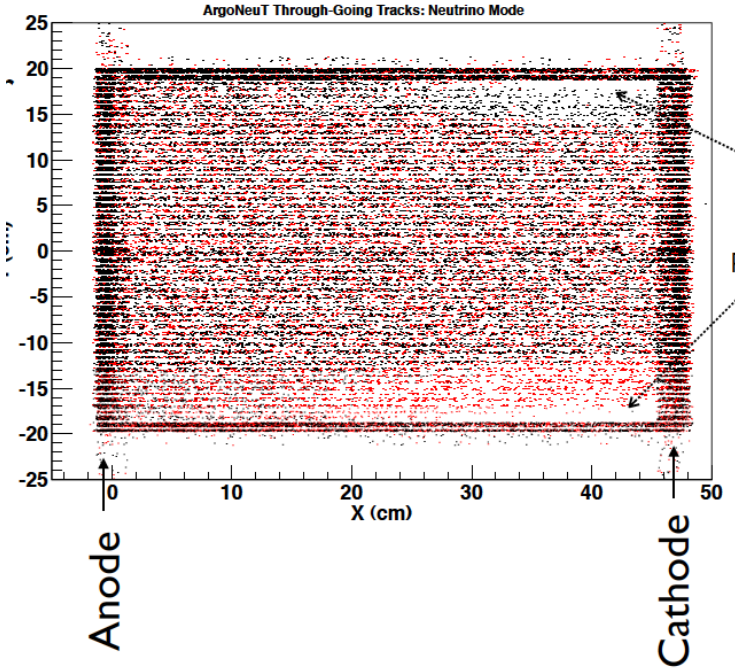
Throughgoing Muons

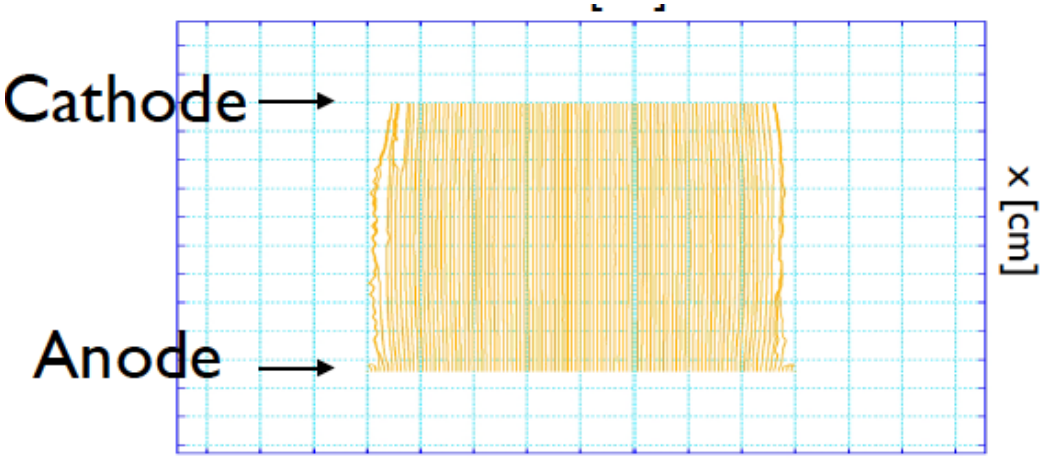
Downward

BUT, with these statistics can also get:

- And some idea of field variations as well



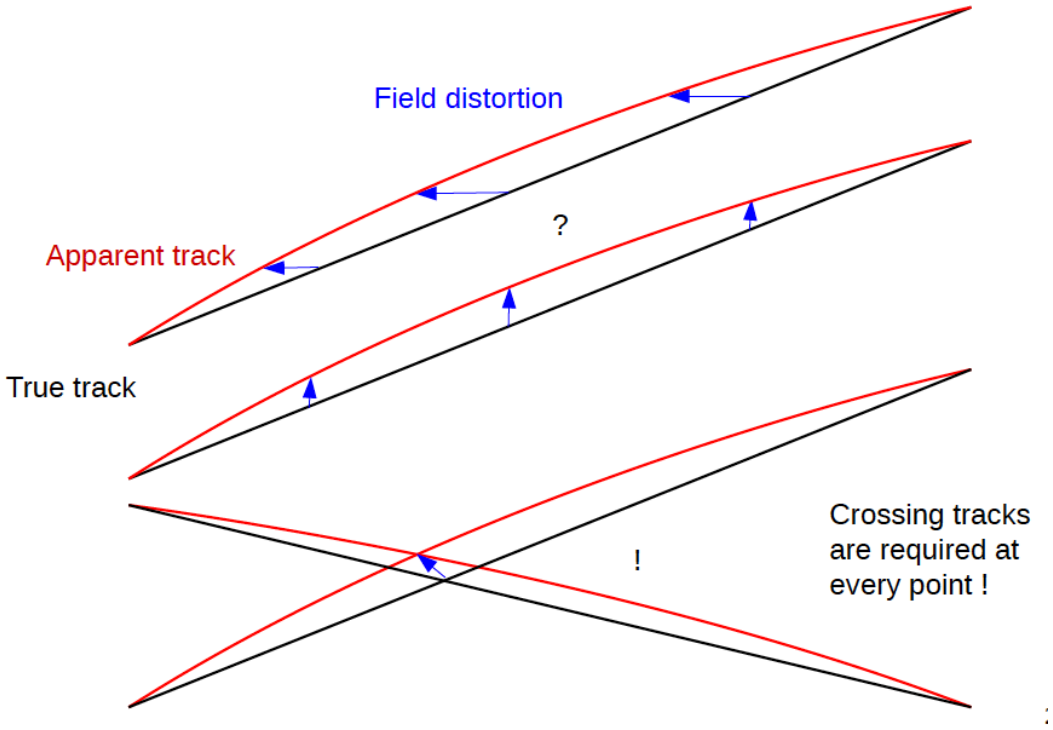




Throughgoing Muons

Downward

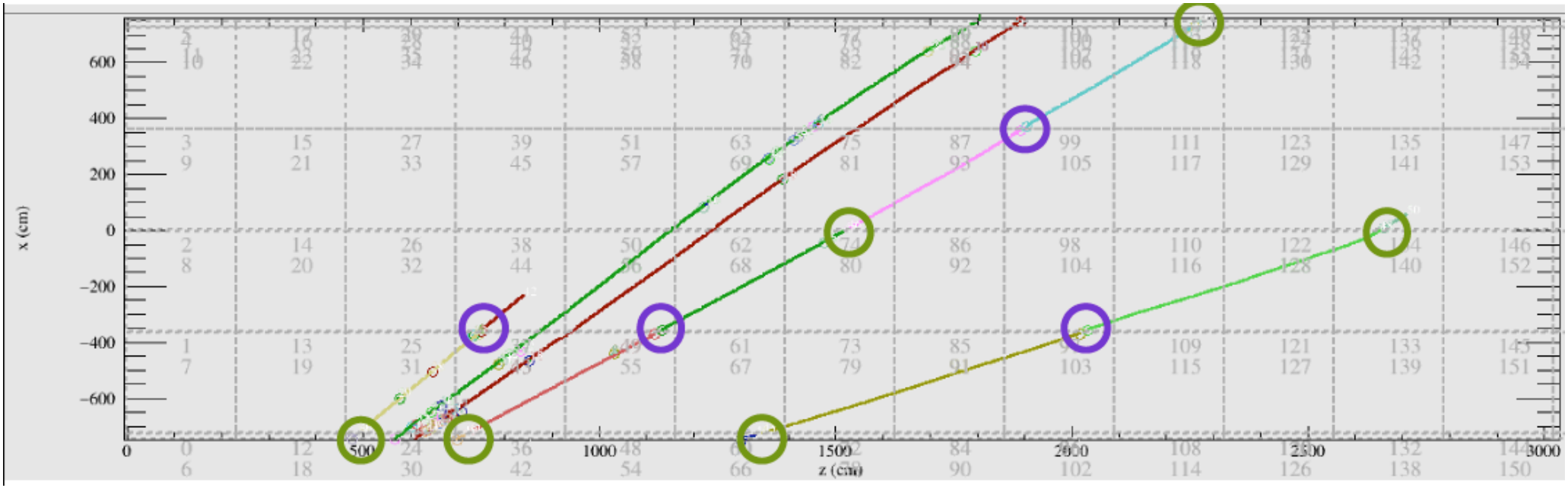
Nevertheless, there are not enough statistics to fully and unambiguously map E(x,y,z,t)---maybe after very long integration time?



Without space charge, we can claim we don't care---
Shhh!! No one will know or will ever check!

Throughgoing Muons

"Crossing"



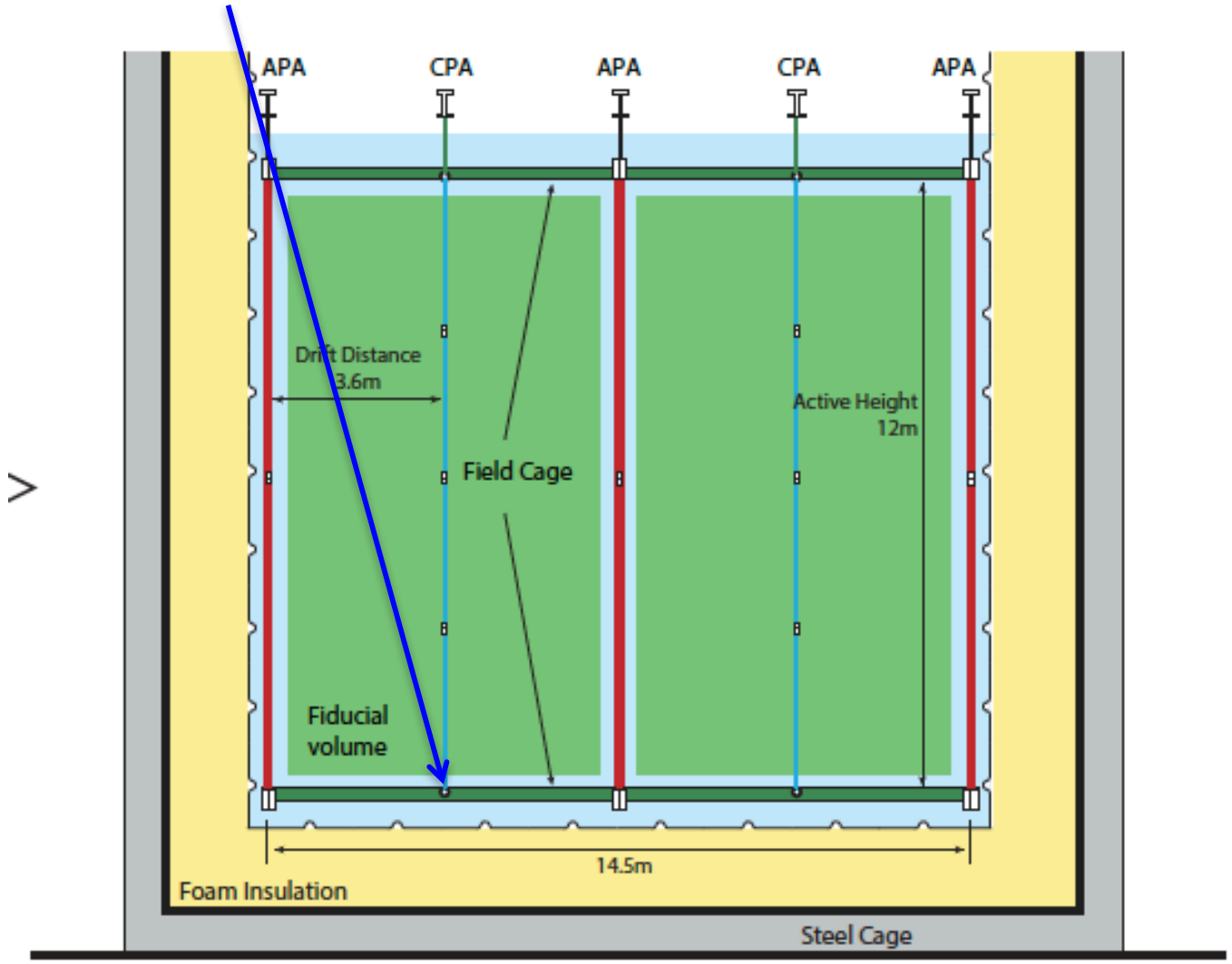
L. Whitehead

Cosmics that cross APAs (3) or CPAs (2) allow us to exploit physical segmentation to get independent constraint on track position without a CRT.

Throughgoing Muons

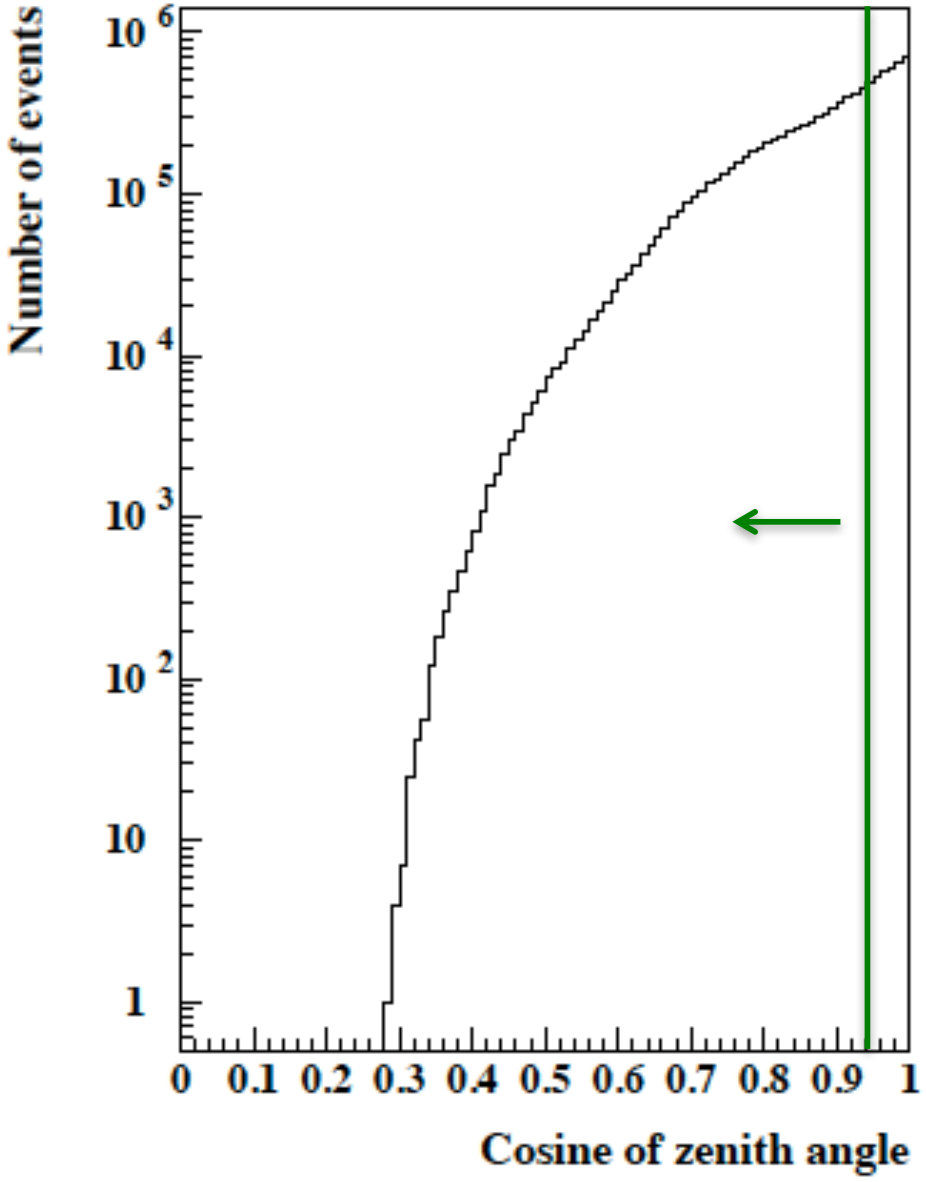
"Crossing"

Steepest angle to cross 1 full TPC is ~17 degrees



Throughgoing Muons

"Crossing"



- About 25% of rate has angles shallower than 17°
- Edges mean not all cross TPCs
- Orientation also means not all cross
- Still, quickly get 1 crosser in each TPC
- (A cosmic that crosses all TPCs has cos(θ) of 0.6)
- Need a t0 from PDS
- Need to have PDS and TPC timed in already

Can measure:

- Lifetime
- Drift velocity
- Diffusion?

What statistics is needed?

Throughgoing Muons

Multiple scattering could help with dE/dx measurement with these; CDR says "to 18%" which is not good enough for anything but a monitor.

These muons do not sample detector in same way that beam events do.

Biases and inefficiencies associated with track geometry will not be well-sampled.

A F-B CRT could allow longitudinal tracks to be used for bias measurements (and veto "dirt" events).

^{39}Ar

- Endpoint of ~500 keV
- Rate in DUNE is 10 MHz=30,000 events in each drift
- In principle uniformity could test recon biases
- But without a t0 have no idea where any given event is
- Way off MIP scale
- Hit just 1(x3) wires; has any LAr-TPC seen these?

Laser System

- Allows plenty of crossing tracks to map electric field
- With a photocathode, can be used to get wire field response
- Could provide diffusion
- But Rayleigh scattering length in LAr for UV is ~18 m for 266 nm
- So single laser across entire volume will be complicated
- In any case, need one for each optically distinct TPC
- Other issues: self-focusing, index variations, beam trajectory measurement

Tagged Events

- Easy-to-ID muons can be used to compare range and energy reconstruction
- If these do not agree…we do what?
- Muon events should not have electrons except through charged π or K decays---test mis-ID?
- π^0 mass peak may not be sensitive to important parameters
- Statistics are only as good as signal events

Need significant analysis effort here

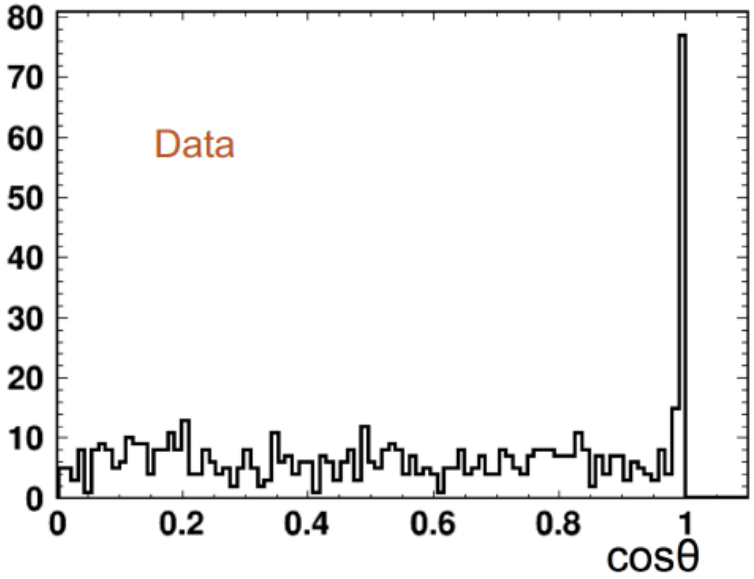
Summary

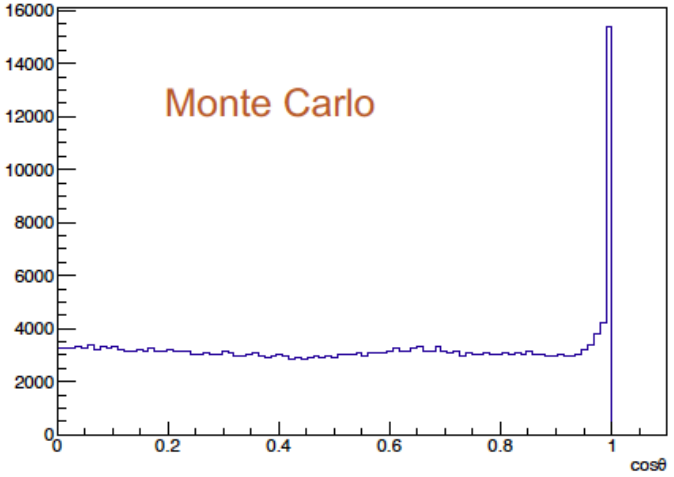
- Will need to calibrate detector in situ
- Can get a lot from crossing cosmics but statistical reqs not known
- No way to get E field without laser---do we care?
- A CRT would allow tests of longitudinal reconstruction biases and provide a second way to calibrate v_d and lifetime.
- Tests with tagged events will be critical but statistics likely to be too small for position- and time-dependent constraints to systematics

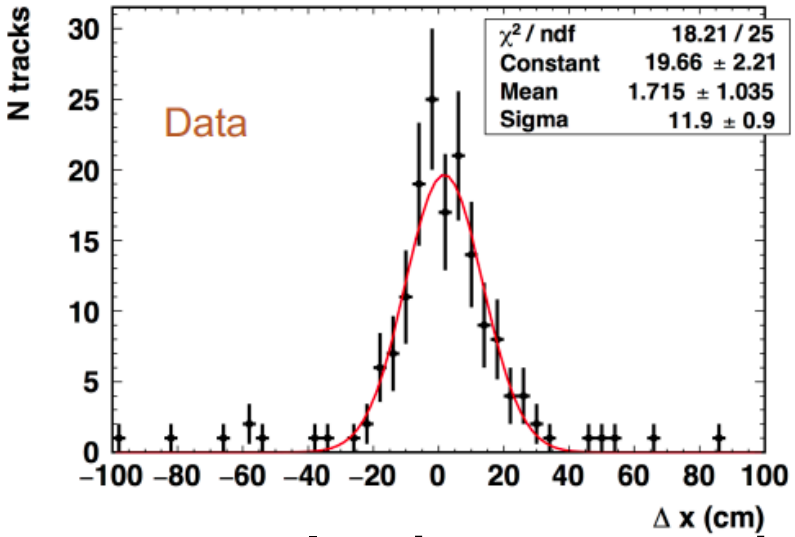
Backups

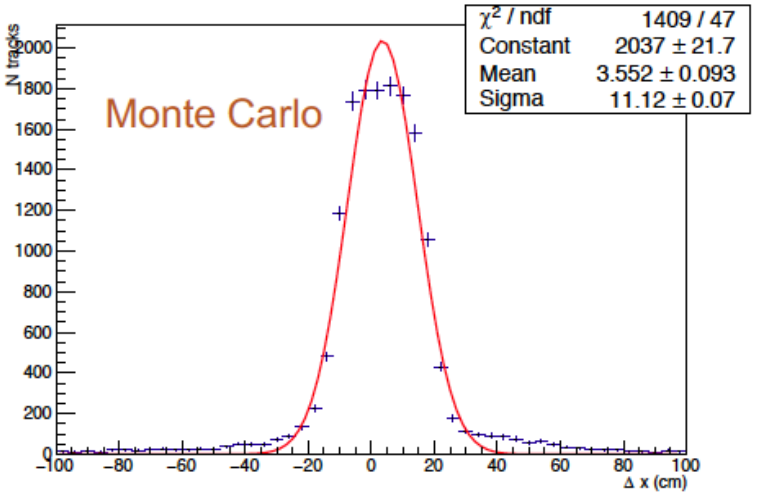
Other Tests

35 t Reconstruction









Agreement looks reasonable, but not final quantitative comparison needed to do physics